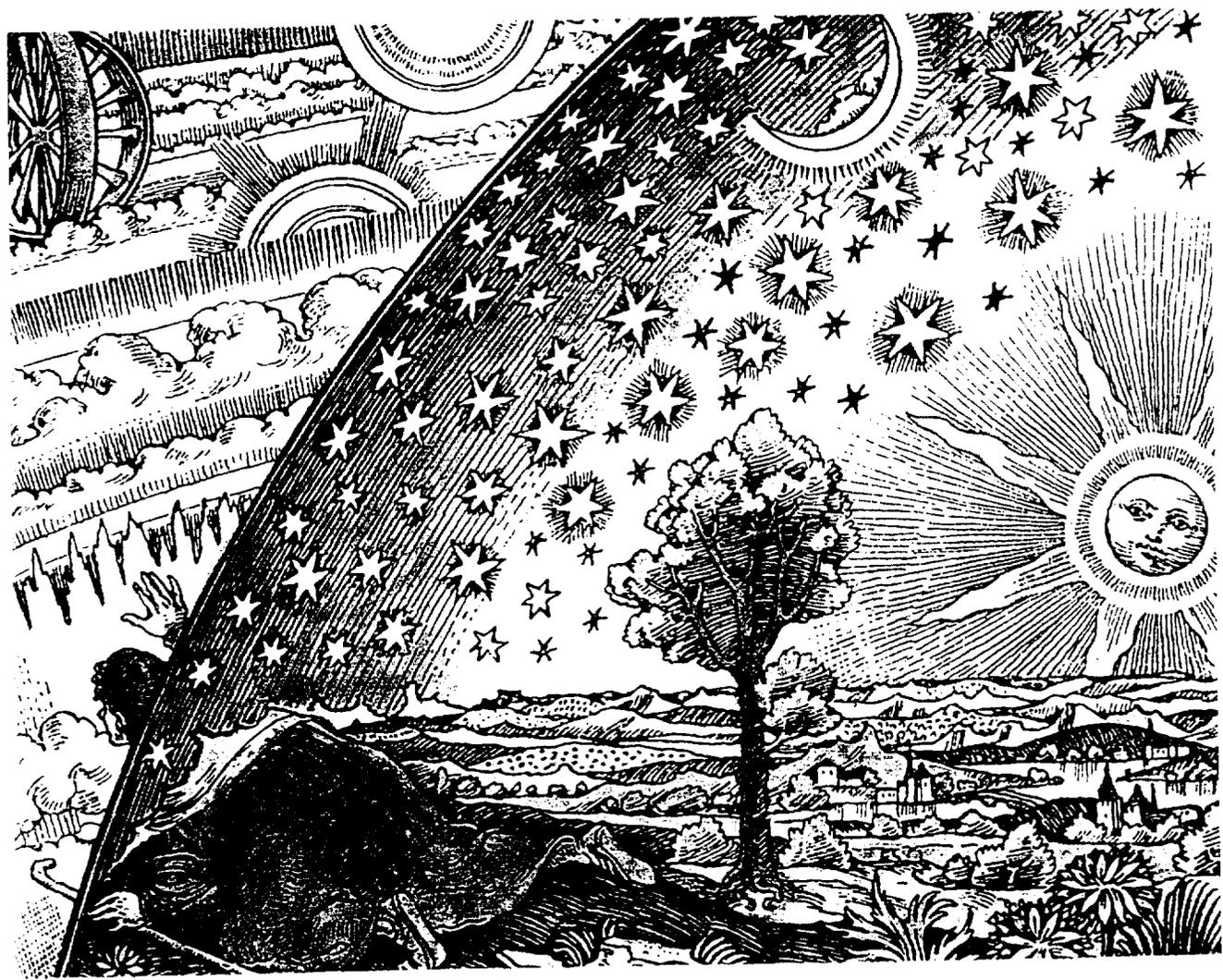


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Understanding Creation: Cosmology at the Dawn of the 21st Century

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*Mankind has forever wondered about the origins of the universe.
New technologies are beginning to probe the details of the
early universe. The results will likely be startling.*



How did the universe begin? How does it evolve? What is our place in it? How will it end? These are ancient questions. We begin to ask them as children, and we remain fascinated with them for the rest of our lives. Metaphysical answers predate recorded history. Now, at the dawn of the 21st century, we are finding the first scientific answers. This is among the most exciting intellectual endeavors of our time. The answers that we find will revolutionize not only our science, but our world-view.

The goal of modern cosmology is to determine the basic properties of the universe that we live in – to find scientific answers to our ancient questions. Hubble's discovery of the expansion of the universe in 1917, not far from where I sit writing this, was the first decisive step towards our current understanding of the universe. It came as a complete surprise to most cosmologists, and it contains an important lesson. Before Hubble's discovery, Einstein had rejected the most natural solutions to his equations of General Relativity because they described universes that either expanded or contracted. He found this idea so absurd that he introduced ad hoc a constant Λ into his equations, modifying them so that they could describe a static universe. We (even the very few Einsteins among us) cannot understand the universe by pure thought. Nature is more interesting than we can imagine.

Hubble's discovery revolutionized the way that we think about the universe. The fact that distant galaxies are moving away from us at a rate proportional to their distance suggests that the universe was once much smaller and denser than it is today. Like all great discoveries, this not only changed our world-view, but immediately led to new questions that had never before been asked. What was the early universe like? What governs the rate of expansion. How old is the universe? How will the universe end?

The full significance of Hubble's discovery remained unclear until 1964, when two radio astronomers, Arno Penzias and Robert Wilson, stumbled onto the second, and arguably the most important, of the major cosmological discoveries of this century: the sky is filled with a uniform glow of microwave radiation. This cosmic microwave background (CMB) is a relic of the primeval fireball that once filled the universe. The early universe was not only dense, it was hot.

Like archeologists, cosmologists try to understand what the early universe was like based on the few fossil relics that remain and the belief that the same laws of physics that we use today apply to the early universe. The CMB is by far the richest fossil find that cosmologists have ever made. The

microwave radiation that we observe today provides us with a direct view of the early universe, at an age long before the first star or galaxy had formed.

The primeval fireball that existed at the moment of creation was a thick soup of energy in the form of fundamental particles and light. While the temperature remained high, pairs of particles and anti-particles were continuously created and destroyed as energy freely shifted back and forth between light and matter. As the fireball expanded and the temperature dropped, most of the remaining particles pairs annihilated with each other, leaving behind only light. At age 4 seconds the fireball had cooled to a temperature at which even the lightest known stable particles – electrons and positrons – were no longer created.

At this point, virtually all of the energy in the early universe had been converted into the light that we observe today as the CMB. A tiny imbalance in the density of particles and anti-particles left a trace residual of matter – about one proton for every 1 billion photons. It is this tiny residual that you and I, and all the stars and planets in the universe, are made of. Were it not for this imbalance, Genesis would read differently, ending abruptly after *let there be light, and there was light*. Though we do not understand exactly why this tiny imbalance existed, we should celebrate it!

By age of 3 minutes, the universe had cooled sufficiently to allow protons and neutrons to fuse into heavier nuclei. This was a high stakes game of musical chairs for the neutrons, which are unstable particles with a half-life of about 10 minutes unless bound into a nucleus. By age 20 minutes, primordial nucleosynthesis was complete. The universe continued to expand uneventfully for the next 300,000 years. Because the matter was in the form of an ionized plasma of electrons and light nuclei, light could not travel very far without being scattered by matter. The universe at this epoch was a thick and opaque fog, not so different from a candle flame.

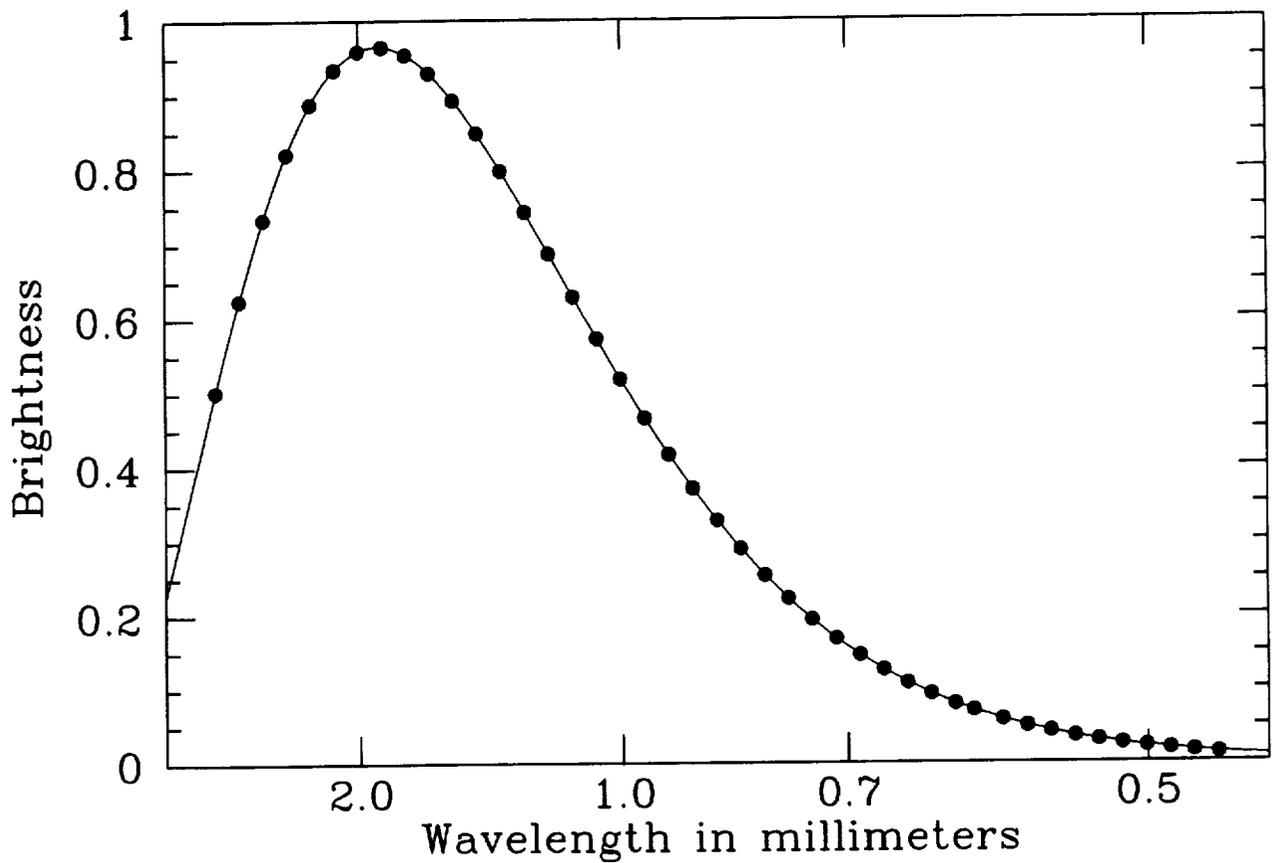
At an age of 300,000 years, the universe had expanded to about 1/1000 of its present size and had cooled to a temperature of about 3000 K (about 5500 F). The originally white-hot fireball now glowed a dull red. At this point in the expansion, the temperature dropped low enough that the electrons and ions combined to form the first atoms. This dramatic event decoupled the CMB from the matter. The thick plasma fog was suddenly replaced by a perfectly transparent gas made up almost entirely of the two lightest and simplest atoms, hydrogen and helium. The universe contained only this gas and light. Light and matter have, to good approximation on the cosmological scale, never interacted since.

When we observe the CMB today, then, we are looking at light that was created during the first minute, and that emerged from the dense fog of the early universe when it was 300,000 years old, some 10 to 20 billion years ago. As a graduate student in Berkeley, I often looked out over the bay and saw the city of San Francisco shrouded in fog. Though the fog prevented me from seeing any detail of the city, it did not alter in any way the orange color of the light that is characteristic of street lamps. I could not see the city, but I could still tell what produced the light. Though the fog that persisted for the first 300,000 years prevents us from seeing details of structure that may have existed before that time, it does not interfere with our ability to determine how the light was produced within the first few minutes.

Pass sunlight through a prism and you will see a familiar rainbow of color. The relative brightness of the various colors is what physicists call a spectrum. If you studied the spectrum of sunlight in detail, you would find that there are tiny bands of color missing from the spectrum. These lines are due to absorption at specific wavelengths characteristic of the atoms in the Sun. These bands tell us precisely how much of each element is contained in the Sun. All objects that emit light – be they the Sun, a light bulb, or the early universe – leave their telltale signature on the spectrum of the radiation. The spectrum of the CMB thus probes the processes that produced it in the early universe.

It is quite difficult to measure the spectrum, and it was not till 1990 that a definitive measurement was made by NASA's Cosmic Background Explorer (COBE). The result is stunning. The spectrum of the CMB is precisely the spectrum that Max Planck had predicted at the turn of the century for an idealized object called a blackbody. A blackbody completely absorbs all light that is incident on it, and emits a smooth spectrum of radiation with a brightness that depends only on the temperature of the blackbody. The CMB approaches this ideal more closely than has ever been measured for any object in any terrestrial laboratory.

The perfect blackbody nature of the spectrum of the CMB tells us two important things. First, the same laws of physics that we derive to explain phenomena observed in the laboratory apply equally well in the early universe. Second, the CMB is a pristine fossil of the early universe, apparently undisturbed by everything that has happened since. These facts together make the CMB our most powerful tool for exploring the early universe. It is as though we had found a 10 billion year old scroll detailing the history of the early universe that it is not only perfectly intact but is written in a language that we can understand.



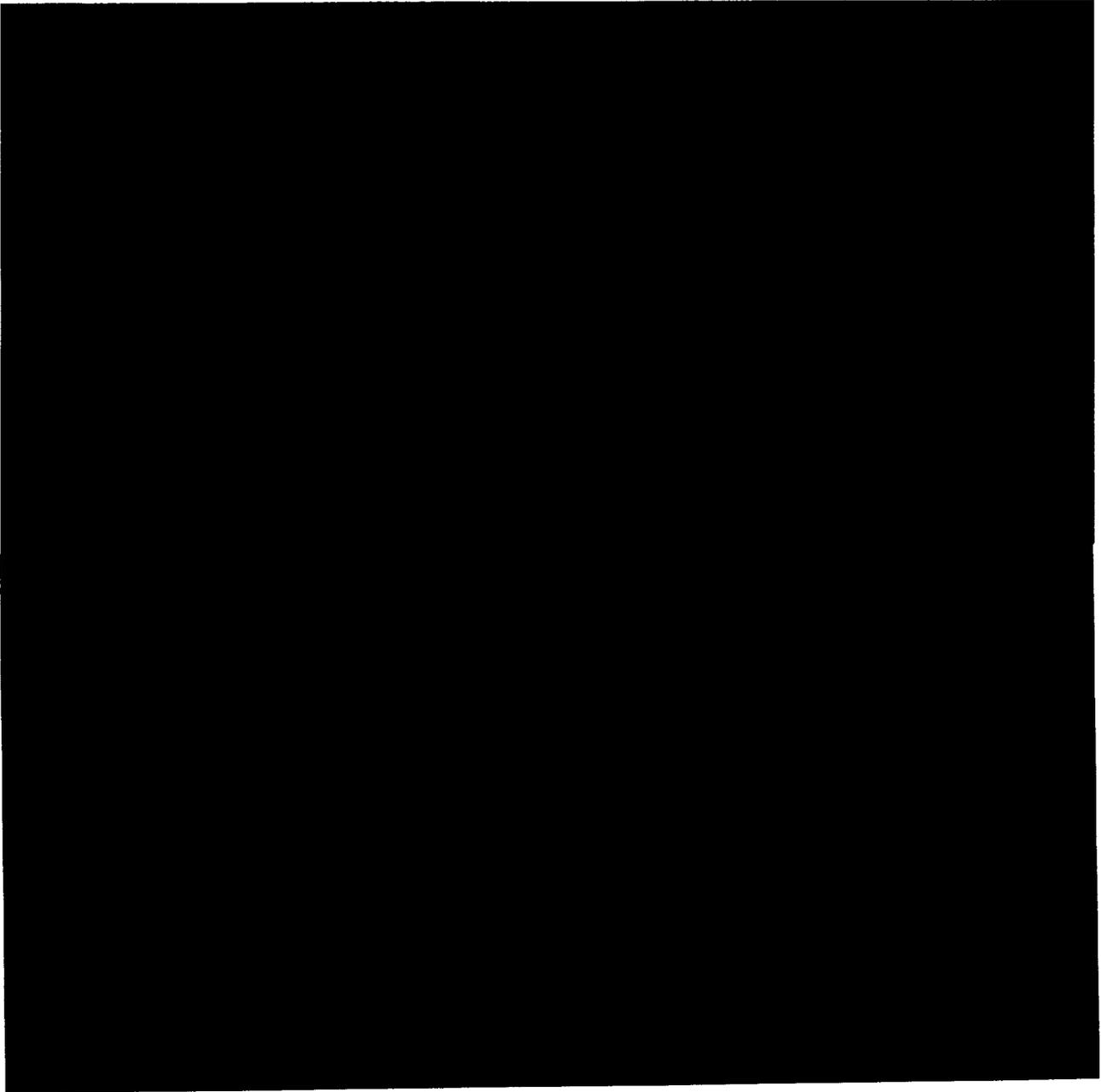
Spectrum of the microwave background. The blue dots indicate the brightness measured at each wavelength. The red curve is the spectrum of an ideal blackbody with a temperature of 2.728 K. The true accuracy of the brightness measurements is much better than indicated by the size of the blue dots. There is no measurable deviation from a perfect blackbody spectrum at the level of 50 ppm of the peak brightness.

The evidence of what happened in the early universe was imprinted in the CMB at the moment of decoupling. It remains preserved there for us to read in the form of small variations in the temperature of the CMB from one part of the sky to another. These variations in temperature correspond to the small variations in density that existed at age 300,000 years, and that would later become the galaxies, clusters of galaxies and larger structures that we see today. The amplitude and the characteristic size of these temperature variations are determined by the detailed evolution of the universe up until the moment of decoupling. Because we can calculate the evolution of the universe with precision over the entire period from the creation of the CMB to its decoupling from matter, the CMB provides us with an archeological record that we can interpret with great accuracy.

What does this record look like? The COBE satellite also carried an instrument which made a map of the CMB. The instrument could not resolve details – the resolution was 7 degrees, about 14 times the diameter of the full moon – but it could detect fantastically small changes in the temperature of the CMB from one part of the sky to another, as small as 20 millionths of a degree. When the effects of our motion are removed, the CMB appears almost featureless. At the very limit of the sensitivity of the maps made by COBE, however, faint patterns of temperature variations appear that cover the entire sky. These patterns are the imprint of the biggest and oldest structures ever seen, vast regions of the early universe that are believed to be the seeds from which everything that we see today evolved.

The Big Bang model is unique among all cosmological models in accounting naturally and precisely for both the expansion of the universe and for the existence of the CMB with its precise blackbody spectrum. It also successfully predicts the relative abundance of the light nuclei that emerged from the Big Bang, and which we can measure today in regions uncontaminated by subsequent nucleosynthesis in stars. The exact ratios of these elements depends solely on the total density of nucleons – what physicists call baryonic matter. The relative abundances of H, D, ^3He , ^4He , and Li agree very well with what would have been produced by primordial nucleosynthesis during the first few minutes after the Big Bang, assuming a narrow range of values for the density of baryons. This is a remarkable achievement, and further confirmation that the laws of physics that apply today, in this case the nuclear reaction rates measured in terrestrial laboratories, apply equally well to the early universe.

It is an enormous intellectual achievement to understand in some detail how the universe has evolved since it was less than one second old. For all of the Big Bang model's successes, however, it also has failures. The



Images of the cosmic microwave background obtained by the Cosmic Background Explorer. Each panel represents a map of the entire sky. The upper image shows the first structure to emerge from the almost featureless background as the contrast is turned up, a smooth sinusoidal variation in temperature between hot and cold poles of 0.007 K, or about 0.2% of the absolute temperature. This feature is believed to be due entirely to our motion relative to the CMB, and indicates that we are traveling at 370 km/sec towards the constellation Leo. The lower panel shows the same map, at 100 times increased contrast. The effects of our motion and emission from our galaxy have been removed. The remaining structures have an amplitude of approximately 0.00003 K, or about 10 parts per million of the absolute temperature. These structures correspond to tiny fluctuations in the density of the early universe.

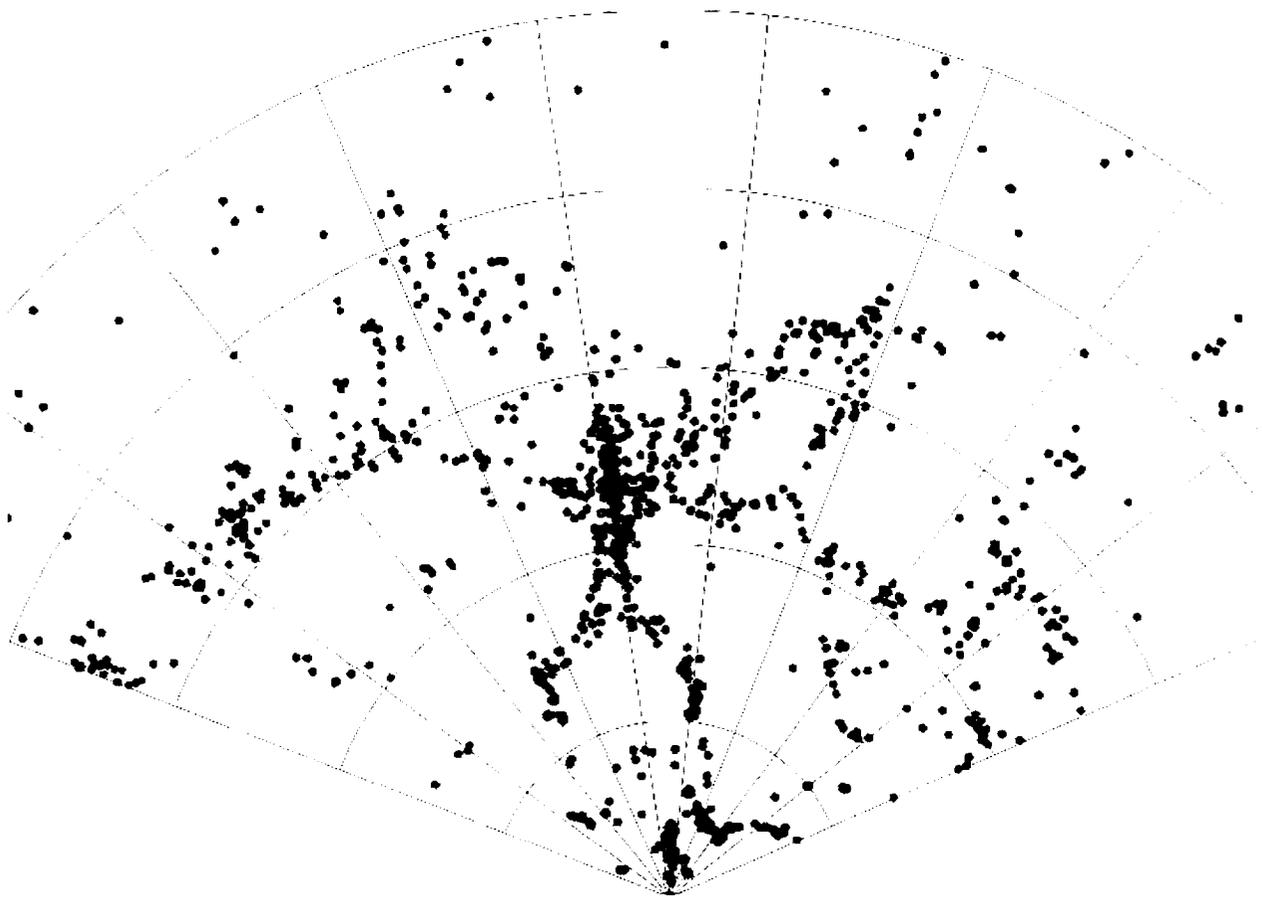
simple Big Bang model that we have described thus far cannot explain several basic observations. In response to these problems, which have come to be known as the Horizon Problem, the Structure Problem and the Flatness Problem, highly speculative modifications to the Big Bang have been proposed that are outside the bounds of conventional physics. The excitement of modern cosmology comes from the fact that we now have the tools to rigorously test these ideas. Like Hubble in 1917 and Penzias and Wilson in 1964, each of whom used new technologies to peer deeper into the universe, we are about to discover something new and surprising.

The Horizon Problem is simply this: the temperature of the CMB that we measure today is 2.728 K regardless of what part of the sky we look at. If the light emitted from two well-separated regions in the early universe is only reaching me now, then there can not have been an opportunity for information to have propagated from one region to another. There has thus been no opportunity for heat to flow between them. How is it, then, that they all have the same temperature?

The Structure Problem is, like the Horizon Problem, a consequence of the extreme uniformity of the CMB. This uniformity tells us that the universe at age 300,000 years was nearly homogenous. One region had the same density as another to better than one part in 10,000. Today, in contrast, we see a rich variety of structure, with large variations in density from one region to another. There are voids which contain almost no galaxies, surrounded by sheets of galaxies that stretch for hundreds of millions of light years. The problem is that, assuming the laws of gravity and the density of matter consistent with Big Bang Nucleosynthesis, you can't get here from there. Structure does not form quickly enough from the nearly homogenous initial condition unless the matter density is significantly higher than the density of baryons allowed by the theory of Big Bang Nucleosynthesis and the measured abundances of the light elements.

Cosmologists usually refer to density in units of the critical density at which the gravitational attraction of matter is just sufficient to eventually halt the expansion. Below this density the universe will expand forever, above it the universe will eventually collapse in a Big Crunch. In these units, Big Bang Nucleosynthesis is consistent with a density of baryons $\Omega_{\text{baryons}} \sim 0.05$.

What is the actual density of the universe? Most matter is not luminous. The only way to detect it is thus to measure the gravitational effect that it has on objects around it. On the scale of galaxies, for example, one can accurately measure the total mass contained within a given radius from the center of the galaxy by measuring the velocities with which the



Distribution of galaxies extending from us outward to a radius of approximately 600 million light years. A region of space this big would subtend about 1 degree in a map of the CMB. We are located at the apex of the wedge at the bottom center of the figure. The map is constructed by using the radial velocity of each galaxy to estimate its distance. The torso and head of the "stickman" in the center of the map is a large cluster of galaxies. Its apparent elongation along the radial direction is an artifact of the map-making technique, and is due to the orbital velocities of the galaxies within the cluster. The distribution of galaxies remains highly inhomogeneous on scales up to hundreds of millions of light years. The contrast between the near isotropy of the CMB and the structure observed in this map poses a riddle – how did these structures form from the near homogenous early universe? (Figure courtesy of Margaret Geller, copyright SAO 1986, original data from Lapporent, Geller and Huchra, 1986)

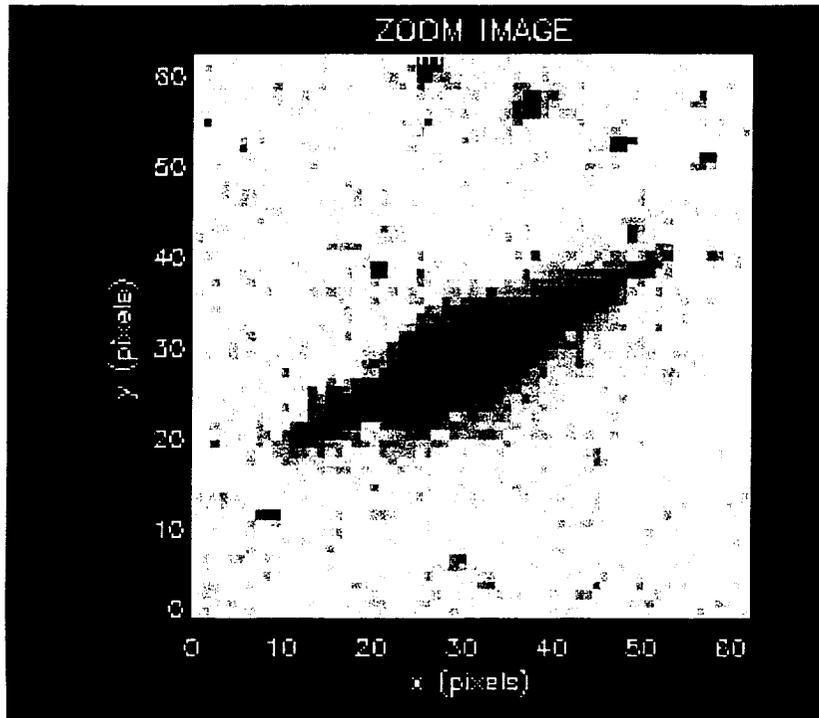
hydrogen gas in the galaxy rotates about the center. The result is surprising. The rotational velocities imply that the bulk of the matter in the galaxy resides in a non-luminous halo that extends far beyond the visible galaxy. The visible galaxy appears to be only the froth on an underlying sea of dark matter.

The exact nature of the matter in the halos around galaxies remains a mystery. If it is normal matter, it is most likely in the form of brown dwarfs (Jupiter-like objects too small to ignite nuclear fusion in their cores) or stellar cinders. Both produce little light, but can be detected by the effect that they have on distant starlight. Light is deflected in a gravitational field. Massive objects thus behave much like lenses, bending light slightly as it passes close to them. If an otherwise invisible but massive object moves through the line of sight to a distant star, then it will focus the light, causing the distant star to briefly brighten. In recent years, physicists and astronomers have painstakingly monitored millions of stars outside of our own Galaxy, and have in fact detected dozens of events which indicate the presence of massive objects in the halo of our Galaxy. The mass of these objects is not well determined, but it seems to be consistent with brown dwarfs. The gravitational lensing data do not yet shed much light on whether there are enough of these objects to account for all of the mass in the halo.

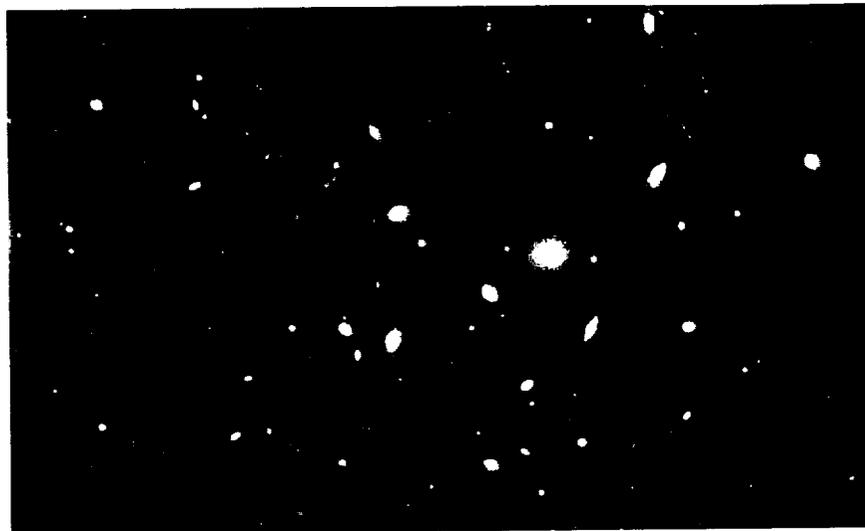
Brown dwarfs are dim, but not invisible. If the halo is made of brown dwarfs, then its faint glow should be detectable at infrared wavelengths. Yet no such emission has been observed, even by very sensitive searches using infrared telescopes in space. The nature of the matter in the halos remains a mystery. The total matter density in the halos of galaxies is large – near the upper end of the range allowed by Big Bang Nucleosynthesis. This raises the possibility that it is not only dark, but that it is not baryonic!

There is evidence for an even greater density of material on larger scales. Galaxies tend to orbit about one another in large clusters. One can measure the total mass in a cluster of galaxies by measuring the orbital velocities of the galaxies. Alternatively, one can measure the mass of the cluster by measuring its effect on the propagation of light rays from more distant galaxies that are aligned with the cluster. Both of these measurements, indicate that there is an even greater fraction of dark matter on the scale of clusters than on the scale of galaxies. On these scales, the density of matter seems to be $\Omega_{\text{cluster}} \sim 0.2$, significantly larger than the density of baryons allowed by Big Bang Nucleosynthesis.

Careful attempts to measure the density of matter on still larger scales result in even larger densities of matter, approaching $\Omega \sim 1$. The trend is



Infrared image of a nearby edge-on spiral galaxy (NGC 4565) recently obtained with a liquid helium cooled telescope carried above the Earth's atmosphere by a sounding rocket. This image, taken at a wavelength of 4 microns, represents the most sensitive search to date for infrared emission from a galactic halo. The experiment is a collaboration between the author's group and the Institute for Space and Aeronautical Science in Tokyo, and uses a sensitive InSb detector provided by Giovanni Fazio and collaborators. The sensitivity of the complete data set obtained during the brief 10 minute flight is so high that the emission from a halo should be clearly evident if it has an average luminosity per unit mass greater than 1/1000 that of the Sun. No emission from the halo is observed.



Rich cluster of galaxies (Abell 2218) as viewed by the Hubble Space Telescope. Most of the matter in the cluster is not luminous. This large concentration of mass, mostly in the form of dark matter, deflects light from more distant objects, and thus acts as a gravitational lens. The extended arcs are the distorted images of galaxies five to ten times more distant than the cluster.

clear: as we probe to larger and larger scales we see evidence for a higher and higher density of matter. At the largest scales the measured density is not consistent with the density of baryons allowed by Big Bang Nucleosynthesis. The Structure Problem thus seems to be not so much a problem of how to form structure, but of what form of matter provides the necessary gravitational force.

The Flatness Problem is related to how the density of the universe evolves with time. If $\Omega < 1$, the density drops as the universe expands, and Ω evolves towards zero. If, on the other hand, $\Omega > 1$, then the expansion will slow and Ω will become larger, since the critical density necessary to halt the now slower expansion is smaller. Only if Ω is precisely equal to unity in the early universe can it remain close to unity later. There is some uncertainty in the present value of Ω , as we have seen, but it is believed to be between 0.2 and 1.5. In order for it to be this close to unity 10 billion years after the Big Bang, at age 1 second it would need to have been 1 to fantastic precision (1 ± 0.0000000000000001). There is no natural explanation in the simple Big Bang model for why this should have been the case. We need to understand why, if the evolution of the universe inexorably pushes the value of Ω away from unity, the value of Ω in the present universe is so close to unity.

The simple Big Bang model provides no solution to the Horizon, Structure and Flatness Problems. There is no way to account for the fact that the density of the early universe appears to have been extremely homogenous and finely tuned to exactly the critical density. Nor, if we believe the limits on the density of baryons set by Big Bang Nucleosynthesis, can the simple Big Bang account for how the structure that we see today formed from these conditions. These are serious flaws that have led to what will someday be viewed as foolishly desperate proposals, or the first inkling of a major new discovery. Both of the proposals involve what happened in the *very* early universe, before age 1 millisecond. Unlike the early universe, from age 1 millisecond to age 300,000 years, the physics of the very early universe is highly speculative.

In 1980 a young physicist named Alan Guth made the remarkable proposal that the fields that governed the interactions between elementary particles in the very early universe were such that the universe had experienced a period of intense pressure – a kind of negative gravity. This phase in the expansion of the universe was unimaginably brief, ending at 10^{-35} seconds, but it had a profound effect on the universe. The pressure accelerated the expansion so forcefully that the universe “inflated” in size by roughly a factor 10^{23} . Regions of the universe that had been in causal contact with one another were pushed away from each other faster than the speed of

light, and so now moved outside each other's causal horizons. As the universe inflated, the density was driven to be exactly unity. At the end of the inflation, at which point our entire observable universe was roughly the size of a grapefruit, the normal expansion resumed.

Though the idea of inflation sounds bizarre, its basic ideas are motivated by ideas from high energy physics. It solves in a single stroke both the Horizon and the Flatness Problems. It also provides a tantalizing idea for why there is something rather than nothing – why we have any structure at all in the universe. As the universe inflates, quantum fluctuations in the energy density on microscopic scales are stretched to span the largest scales we see today. If this picture is correct, then the enormous structures of galaxies that span more than 100 million light years in the present universe are remnants of microscopic fluctuations driven by the Heisenberg uncertainty principle during the inflationary epoch.

The second idea to emerge from the era of speculative physics is that most of the matter in the universe today is in the form of elementary particles that we have never detected. Unlike inflation, this strange new idea cannot be viewed with the intellectual detachment provided by 10 billion years distance in time. This exotic matter, if it exists, streams through your body as you read this essay.

From the perspective of a particle physicist it is quite plausible that the early universe would produce not only the protons, neutrons, electrons, neutrinos and photons that we know exist, but also some much heavier stable particles. If these exotic particles had an electric charge or interacted strongly with ordinary matter, then they would have been detected by now in the laboratory. If, however, these particles interact only weakly with other matter – as does the neutrino, for example – then the universe could in fact contain a very high density of them without our being aware of them.

Weakly interacting particles would provide just the sort of matter necessary to solve the Structure Problem if they were massive enough to be “cold” – that is to be moving at non-relativistic speeds. If we assume that they exist, and that inflation occurred, then we can build a cosmological model that is reasonably consistent with all observations to date. This model has come to be known as the standard Cold Dark Matter model. The cosmological literature today is full of calculations describing the properties of such universes.

The reader is forgiven for being skeptical at this point, and perhaps unimpressed by the ability of cosmologists to square their theories with

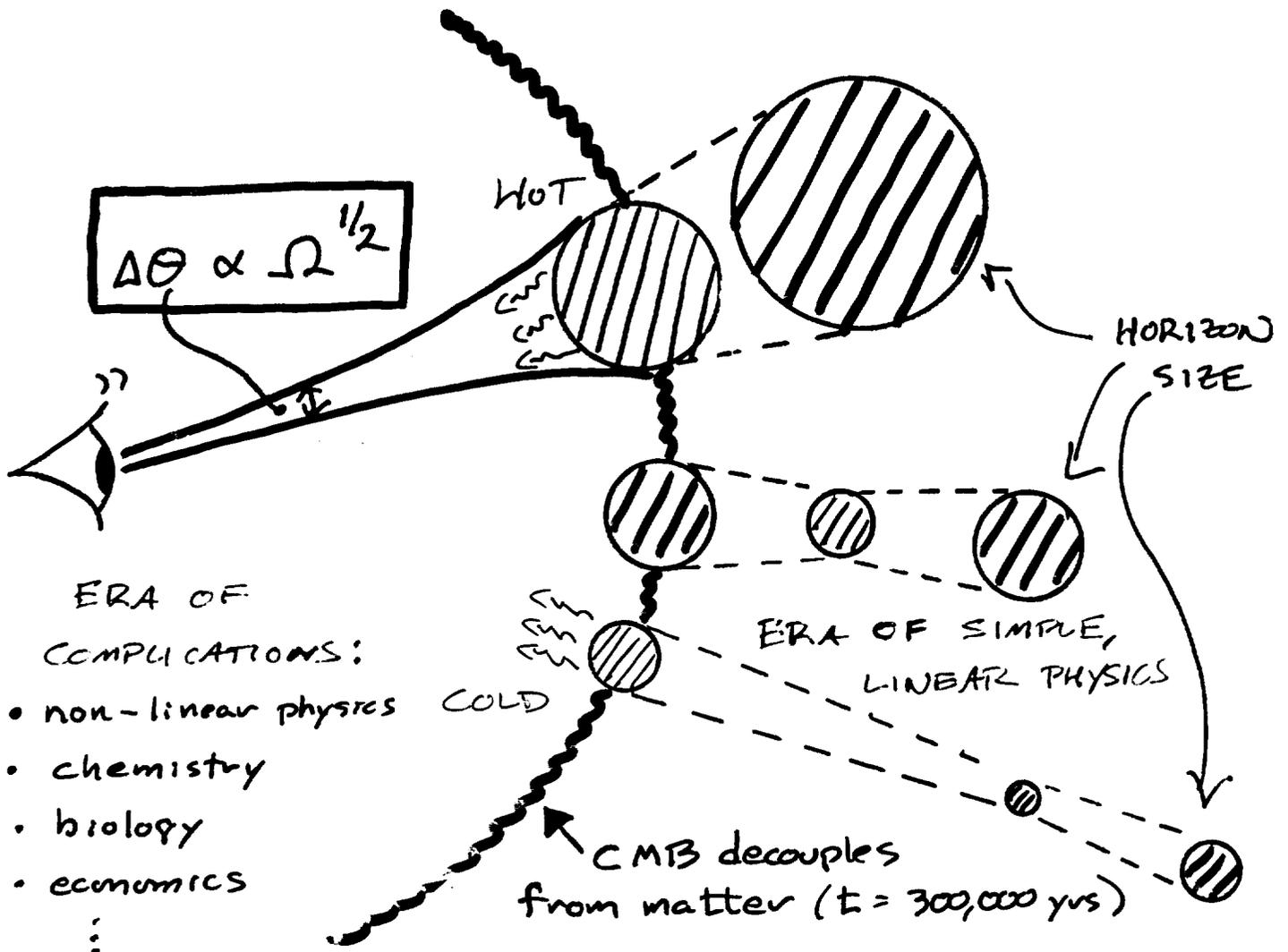
observation by invoking a superluminal expansion of the early universe, and claiming that the dominant form of matter in the universe is an exotic particle that has never been detected. We would do well to remember that theoretical speculation unchecked by observation is usually wrong. As much as theorists are enamored by the idea that $\Omega = 1$, there is as of yet little observational evidence, and only speculative theoretical reasoning, to support this claim.

This is the state of cosmology today. In contrast to the major successes of interpreting the expansion, the CMB, and the relative abundance of the light elements, all of which are firmly grounded in known physics, the recent modifications to the Big Bang model border on metaphysics. They would be of no real scientific interest unless we had a way to rigorously test them (and the yet unproposed alternatives that will likely emerge when we do!). The CMB contains imprinted in it the information that we need to perform this rigorous test. The information is, however, in very fine print, not discernible in the COBE maps.

As the early universe expanded, self-gravity caused overdense regions to contract. This is the basic process by which we believe all structure formed out of what was initially a nearly homogenous distribution of matter. Two facts about the early universe are important to understand. First, a region cannot start to collapse until it “knows” that it is overdense. Since the effects of gravity travel at finite speed (the speed of light) small regions begin to collapse before large regions.

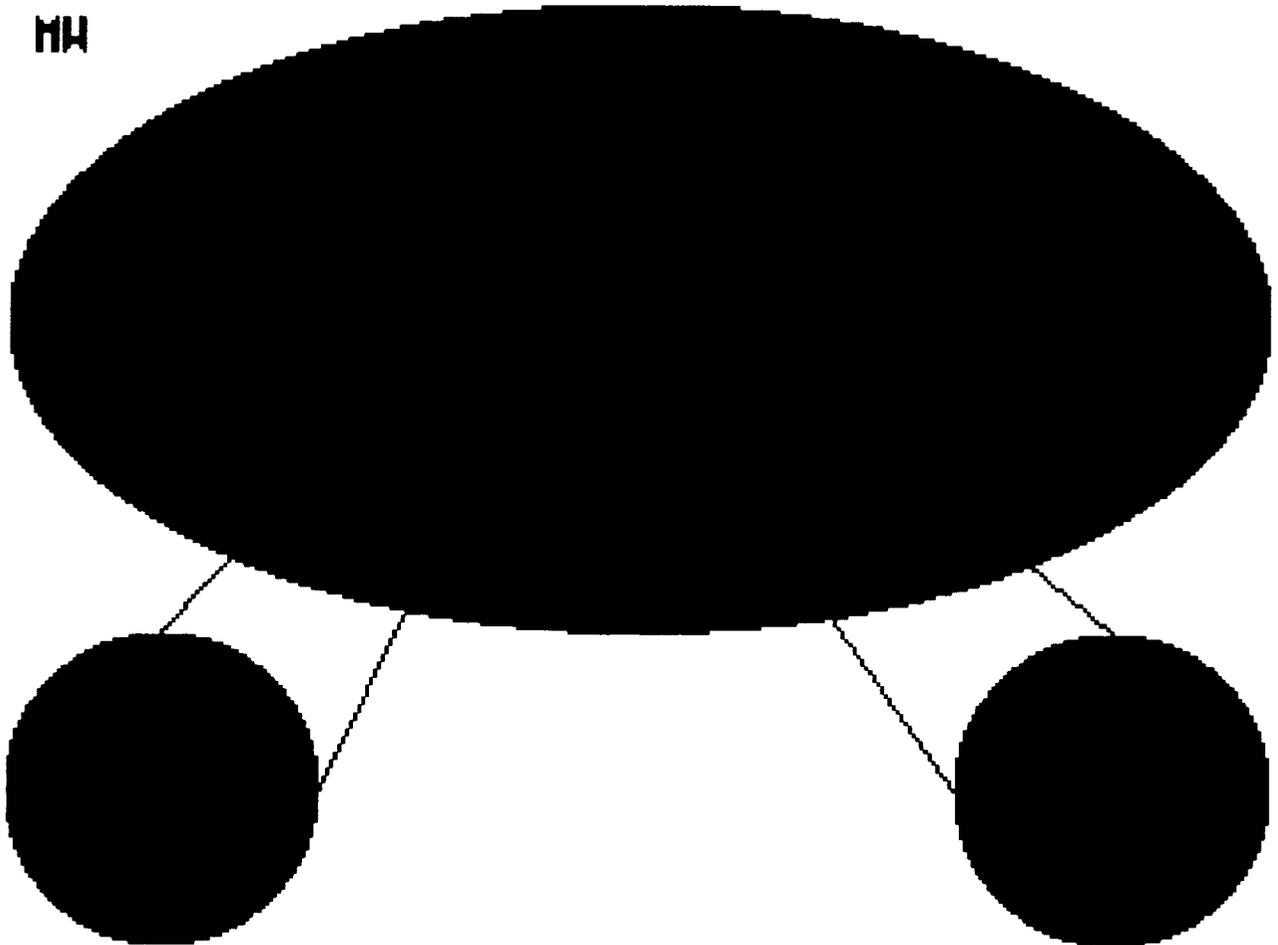
The second fact is that matter and radiation in the early universe, before decoupling at age 300,000 years, formed a tightly coupled fluid. As an overdense region began to collapse, the pressure of the radiation grew, resisting the collapse. The competing forces of gravity and radiation pressure caused each region that had begun to collapse to oscillate in size, alternately contracting and expanding.

Imagine then a number of regions of different size. There is a maximum size region which, having begun to collapse at a rather late age, happens to reach a state of maximum compression (and high temperature) precisely at the moment of decoupling. This size of this region at that moment sets the largest characteristic scale that is imprinted on the CMB. Similarly, there is a smaller size region that, having begun to collapse earlier, has gone through 3/4 of a full oscillation, and finds itself at in a state of maximum rarefaction at decoupling. The size of this region sets the characteristic scale of the largest cold spot.



Cartoon of the formation of structure in the CMB shows how oscillations in the photon-baryon fluid before decoupling create specific length scales for hot and cold regions that are frozen into the CMB at decoupling. The size and amplitude of the structures depend sensitively on most of the fundamental cosmological parameters, and can be accurately calculated because the universe prior to decoupling is governed by simple linear equations. The characteristic angular diameter and the amplitude of the features in the CMB that we see today thus directly probe the early universe.

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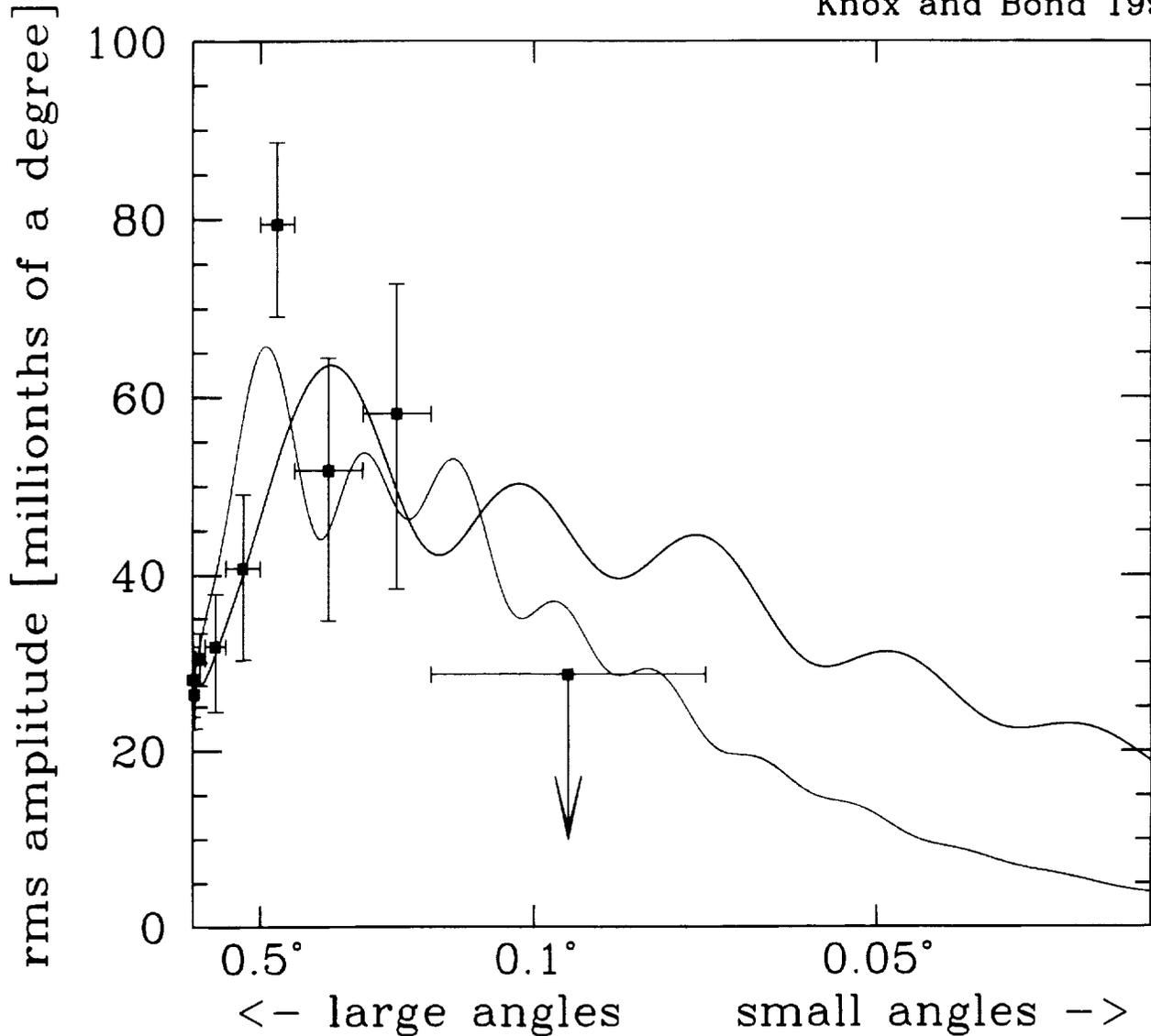
The fine scale structure of the CMB predicted for universes with densities $\Omega = 1$ (left) and $\Omega = 0.1$ (right). The two insets show the type of structure that would be seen in a single 7 degree diameter patch of the sky (equivalent to the angular resolution of COBE) for each universe. The increased structure on smaller scales in the $\Omega = 1$ universe is immediately evident. Mathematical analysis of a map of the entire sky with this angular resolution and sensitivity should provide enough information to determine the total density of the universe (and thus determine whether it will expand forever) and what fraction, if any, of the total density of the universe is in an exotic form of matter. (Image courtesy of Martin White)

In detail, the exact size and amplitude of the various hot and cold spots depends on the density of baryonic matter and the expansion rate, as well as other cosmological parameters. How big do these regions appear today? Recall that light is deflected by the net gravitational effect of all of the matter and energy along its path. Thus, the apparent angular diameter of a distant object depends on the total matter density Ω . The apparent angular size that these regions have when we view them from a distance of some 10 billion light years depends then not only on their physical size at decoupling, but also on the total density of all matter in the universe.

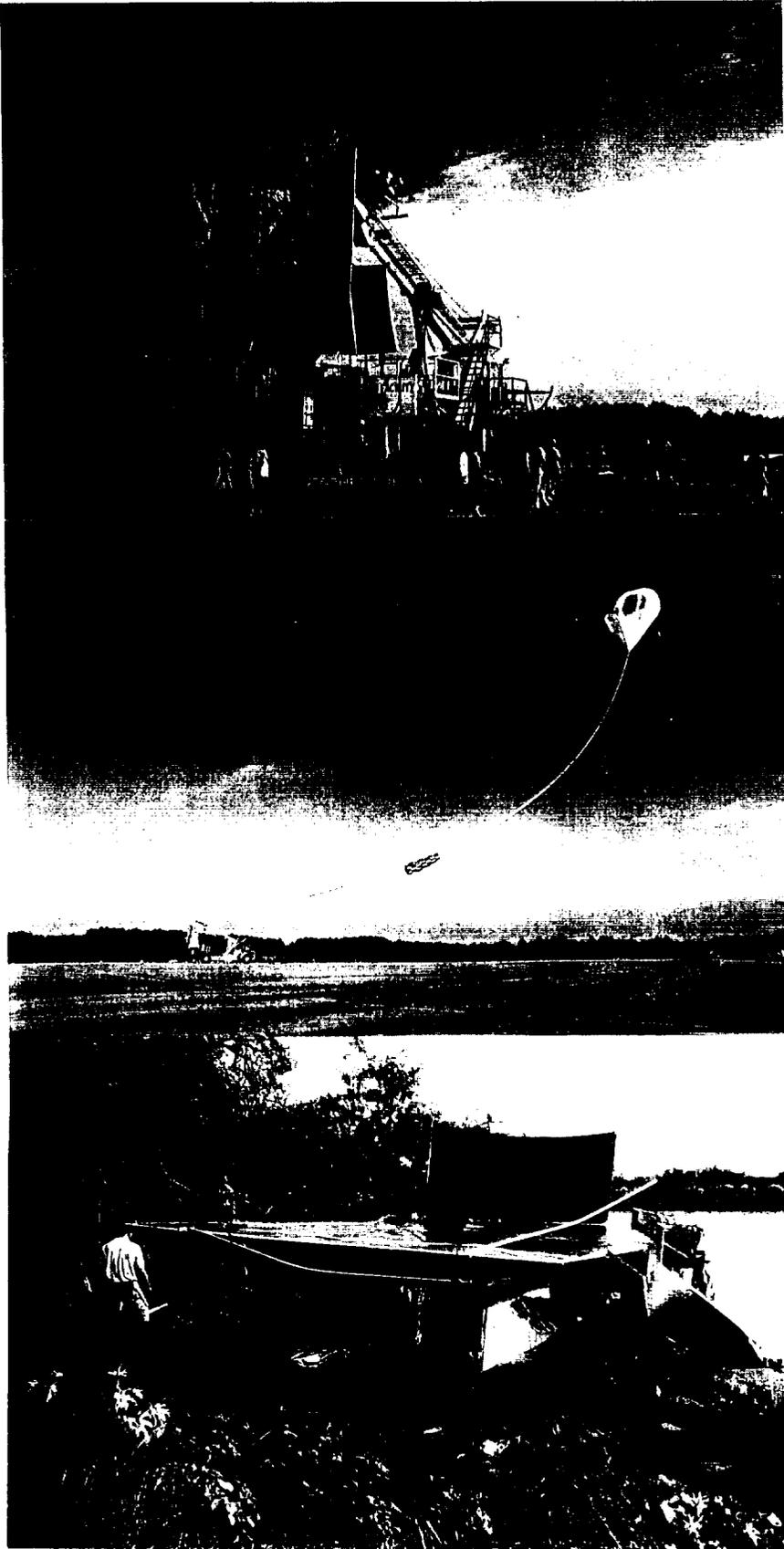
When all of the details are worked out, the theory predicts a series of characteristic angular scales, ranging from about 0.5 degrees (the size of the full moon) to about 0.05 degrees. Only the vaguest outlines of these structures can be seen in the COBE maps. When we are able to observe all of the fine details in the CMB sky, it will look quite different than the COBE map. There will be a rich variety of structures on scales almost as fine as the resolution of our eyes, the exact size and amplitude of which contain a precise inventory of the contents of the universe.

We will not, of course see " $\Omega = 1$ " writ large on the heavens, at least not literally. The information that we are after is not contained in the positions of the hot and cold spots, which are distributed randomly, but rather simply on the relative number and amplitude of spots of a given size. This information can be extracted mathematically from the map very much as a piece of music can be decomposed into the relative amplitude of tones that it contains. In this analogy, the COBE maps contain only about 20 bass notes. The characteristic features that we expect to find are distributed over more than 1000 treble notes.

Many groups around the world are now working at a furious pace to map enough of the sky in enough detail to measure these features in the CMB. These measurements are difficult to make. The features that we seek to measure are almost a million times less bright than the Earth's atmosphere. Physicists are thus going to great lengths to deploy telescopes with sensitive receivers at extremely high and dry sites in the Chilean Andes and at the South Pole, and even on high altitude balloons over the Antarctic. These experiments should measure the characteristic size of the structure in the CMB with enough precision to easily distinguish between models with $\Omega = 1$ and models with $\Omega \leq 0.1$. They will thus determine, if one believes in the calculations of Big Bang Nucleosynthesis, whether or not we are made of the stuff that most of the universe is made of.



The amplitude of temperature variations in the CMB as function of angular scale. The characteristic angular scales and amplitudes of structure depend sensitively on the fundamental cosmological parameters. Most models predict a harmonic series of characteristic angular scales starting at a fraction of a degree and extending to smaller scales. The blue curve represents the standard Cold Dark Matter model currently favored by most cosmologists, with $\Omega = 1$ and 20 grams exotic matter for every 1 gram baryonic matter. The red curve is a variant of this model with $\Omega = 0.33$ and 10 grams exotic matter for every 1 gram baryonic matter. The green points indicate the current state of our knowledge. The left most point represents the information from COBE on large angular scales. Other data has been obtained more recently by a variety of ground-based and balloon-borne telescopes. Note that the upper limit on the amplitude of structure on the smallest angular scales is a powerful discriminant between these two models, and favors the $\Omega = 1$ universe. This upper limit has been independently obtained by two experiments at Caltech, using telescopes in the Owens Valley and on Mauna Kea, Hawaii. The yellow shaded region indicates the ultimate precision which will be obtained by the Planck Surveyor, using detectors built by the author's group at Caltech. This measurement should determine all of the cosmological parameters to high precision. (Figure courtesy of Lloyd Knox)



Physicists are now going to great lengths to map the CMB with the sensitivity and angular resolution necessary to determine what the universe is made of. The upper panel shows BOOMERANG, a 1.3 m telescope equipped with a dozen bolometric detectors of the type that will someday fly on the Planck Surveyor. BOOMERANG is designed to circumnavigate the Antarctic during a 10 day voyage on a high altitude balloon. The middle panel shows the payload being launched on its maiden test flight in Palestine Texas in August 1997. This flight ended abruptly due to a faulty balloon. The bottom panel shows where the telescope landed. Remarkably, the payload was recovered, refurbished and flown again just two weeks later. The second flight worked well. BOOMERANG is now being readied for its maiden Antarctic flight. BOOMERANG has been developed by the author's group in collaboration with groups in Berkeley, Florence, Rome, and Santa Barbara.



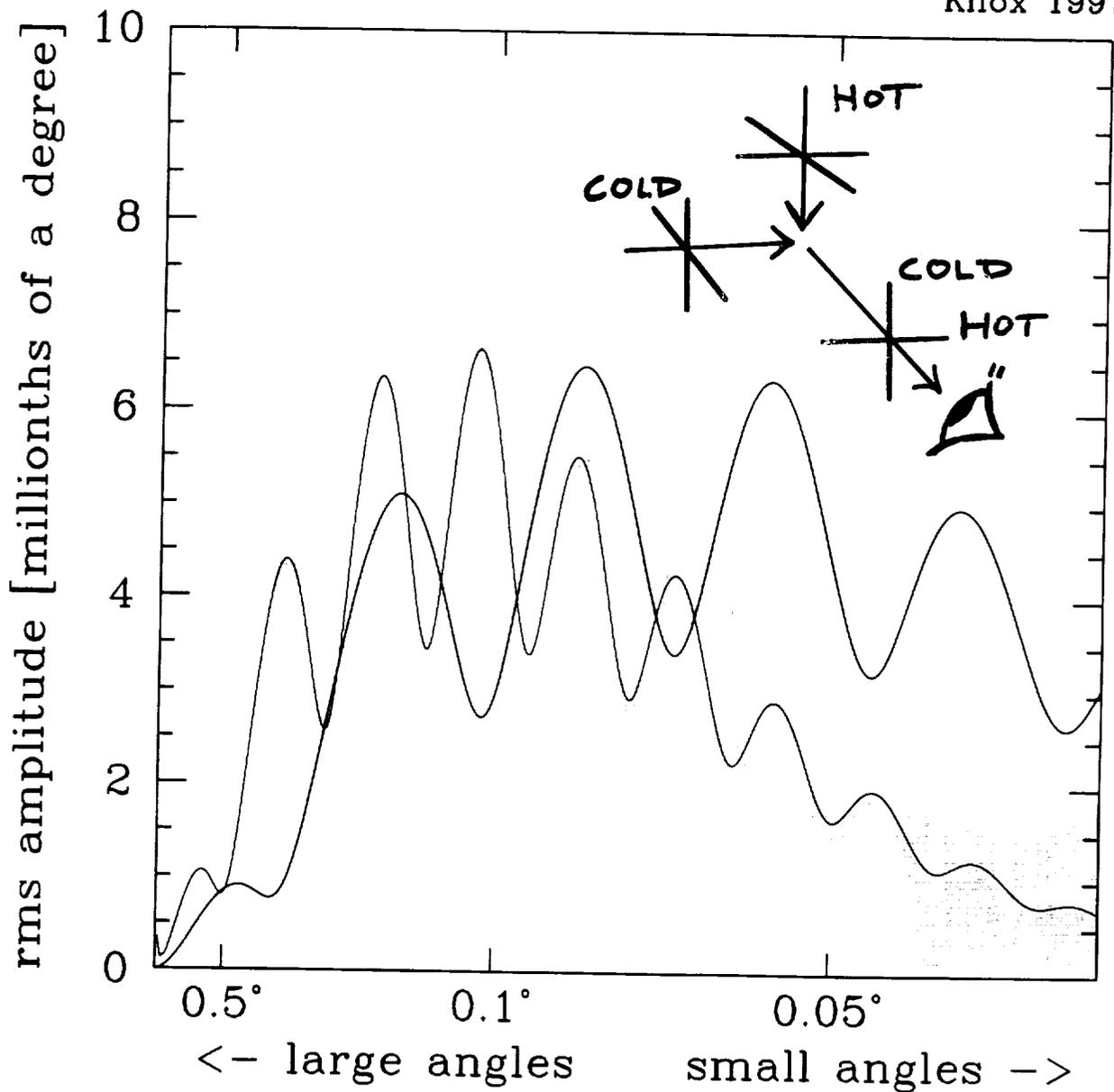
Bolometric detector of the type that will be used on the Planck Surveyor. The "spider-web" structure is a free-standing mesh of micron scale beams that efficiently absorbs CMB radiation but is largely transparent to cosmic rays. The temperature rise of the web is measured by a small thermistor at the center. These devices operate at 0.1K and are the most sensitive detectors of the CMB yet developed. They will play a crucial role in our investigation of the early universe.

Such experiments are only possible because of the great improvements in detectors that have been made in the last few years. The most sensitive detectors now available achieve a sensitivity over 100 times greater than the detectors used by COBE. Both NASA and ESA (the European Space Agency) have begun to design and build new satellites that will take advantage of these advances in technology to provide maps of the entire sky with much greater detail than the COBE map. Each of these satellites will be launched into an orbit a million miles from the Earth, in the direction opposite the Sun. From this vantage point, the Earth will appear only about as big as the full moon, giving the telescopes a clear view of the CMB. The first of these telescopes, MAP, will be launched by NASA in 2001. The second, the Planck Surveyor, will be launched by the ESA 4 years later, in 2005. The Planck Surveyor will ultimately provide the most detailed map of the CMB, by using detectors cooled to just 0.1 K.

Both of these experiments, and others that will attempt to map large portions of the sky from ground-based and balloon-borne telescopes, promise to transform cosmology. Though few of the cosmological parameters have ever been successfully measured with an accuracy better than 50%, the experimentalists and theorists working on the design of these CMB experiments hope to be able to determine most of the cosmological parameters with an accuracy approaching 1% or better. The history of cosmology teaches that, if we are successful at learning so much about the universe, we should expect to be surprised at what we find.

We should also plan on being skeptical of the results. Nature's ability to be more interesting than we can imagine could wreak havoc with our plans to make precise measurements of the early universe. At the high levels of precision that we hope to achieve, how can we ever be completely confident that the information encoded in the CMB has been preserved uncorrupted for billions of years and, if so, that we have properly interpreted what it is telling us? One should always be suspicious that an ancient scroll purporting to reveal the secrets of the universe is a forgery. Fortunately, Nature has provided a way to check the authenticity of the CMB.

Light consists of electric and magnetic fields, each field oriented perpendicular to the direction of propagation of the light. The orientation of the fields in the plane perpendicular to the direction of propagation is normally random. In some cases, however, the electric field is preferentially oriented in one direction. Such radiation is said to be polarized. We often encounter polarized radiation in our everyday lives. Light reflecting at grazing incidence from a surface has the electric field oriented perpendicular to the surface suppressed, and thus emerges from the reflection partially



The predicted amplitude of polarization in the CMB as a function of angular scale. The blue curve represents the standard Cold Dark Matter model currently favored by most cosmologists, with $\Omega = 1$ and 20 grams exotic matter for every 1 gram baryonic matter. The red curve is a variant of this model with $\Omega = 0.33$ and 10 grams exotic matter for every 1 gram baryonic matter. Both the amplitude and the characteristic angular scales predicted for CMB polarization are smaller than those predicted for temperature fluctuations. No detection of polarization has ever been made. The yellow shaded region indicates the precision with which the polarization could be measured using recent breakthroughs in bolometric detector technology and a dedicated 6 m telescope at a high and dry site such as the Atacama desert in the Chilean Andes. (Figure courtesy of Lloyd Knox)

polarized. The glare of sunlight reflecting off of a lake is polarized in this way and thus Polaroid sunglasses, which preferentially block one polarization of light, can efficiently reduce the glare. (Try the experiment of turning your head sideways and you will see that they no longer work so well.)

If our interpretation of the CMB is correct then, like the glare of sunlight reflected off of the surface of a lake, the CMB will be partially polarized to a degree that is precisely related to the amplitude of the temperature variations themselves. This is because the two polarizations that we observe today reflect the temperature of the sky that an observer present at decoupling would measure in two orthogonal directions. The amplitude of polarization has a dependence on angular scale that is different from, but uniquely related to, the characteristic angular scales of the temperature variations.

A precise map of the polarization of the CMB would provide a powerful and important test of the whole framework of our interpretation of structure in the CMB. It would also enable the cosmological parameters to be determined with even greater accuracy, since it provides more information than is available from a measurement of the temperature structure alone. To make such a map will be an enormous challenge. The amplitude of the expected polarization is only a few millionths of a degree – fully ten times smaller than the temperature variations. In addition, the characteristic angular scales are smaller, requiring a measurement with finer angular resolution.

For these reasons, the polarization signal is very difficult to detect. No polarization has been detected to date, and neither of the planned satellites will be able to measure the polarization with precision. Despite this, there is good reason to believe that we will succeed in mapping the polarization of the CMB within the next decade. Measurements of the temperature variations of the CMB using telescopes on the Earth's surface are limited by the effects of the Earth's atmosphere. Because the emission from the atmosphere is not polarized, however, the higher sensitivity that is required can in principle be achieved for polarization measurements with ground-based telescopes. A telescope in the Owens Valley in California that has been carefully optimized for measurements of CMB temperature variations at small angular scales is now being equipped with new, polarization sensitive instrumentation based on the very sensitive detectors that our group has developed for the Planck Surveyor. The combination of this telescope and the new detectors should allow the polarization of the CMB to be detected in a single season of observing.



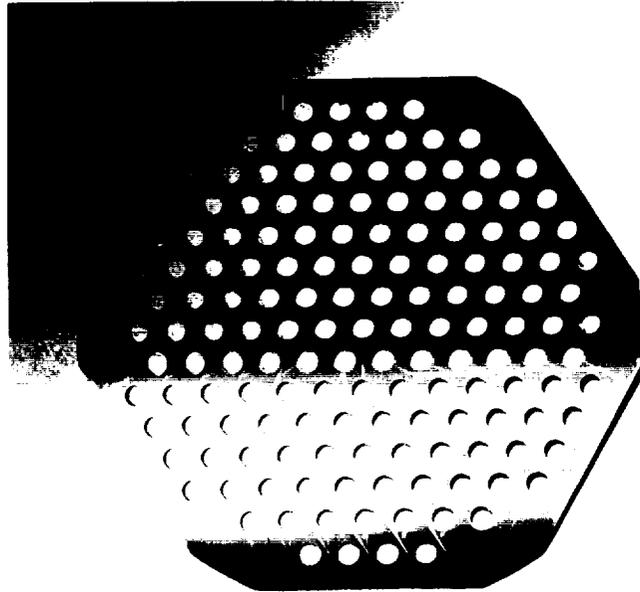
The Caltech 5.5 m CMB telescope, located in the Owens Valley. This telescope, which has been carefully optimized for observations of the CMB, is now being outfitted by the author's group with new instrumentation designed to detect the polarization of the CMB on arcminute angular scales. This experiment should be capable of detecting the polarization of the CMB on arcmin scales in a single season of observing.

A definitive measurement of the polarization – one that measures not just detect the presence of polarization but can measure the characteristic angular scales as well, would take decades of observing with the instrument that is currently being built in the Owens Valley. Fortunately, technology is advancing so rapidly that even now, before observations in the Owens Valley have begun, a new technology is becoming available that will increase the speed with which the sky can be mapped by a factor of 100. Hundreds of sensitive bolometric detectors can now be produced on a single wafer of silicon. A receiver built using this technology and placed on a dedicated telescope at a site in the Chilean Andes, could achieve a definitive measurement of the polarization in a single year of observing.

When we have succeeded in measuring the amplitude and the characteristic angular size of both the temperature variations and the polarization of the CMB, then we will have succeeded in reading all of the information that was imprinted on the CMB at decoupling. In addition to this information about the early universe, however, there is more information contained in the CMB that, like margin notes found in an ancient manuscript, has been added over the passage of time. This information is important. It can reveal features of the universe since decoupling which we have no other way of knowing.

A cosmological model must explain not only why the universe was the way it was at age 300,000 years, but also how it evolved from that nearly homogenous state to its present form – i.e. the model must provide a convincing answer to the Structure Problem. At first glance, making the leap of faith that the universe contains a large amount of exotic matter solves the Structure Problem. Simulations show that the universe can form structures that look more or less like the structures that we see today, provided that it contains an appropriate type and density of exotic matter. There is one aspect of this solution that is unsatisfying, however. By postulating that most of the universe is in a form that we do not see, we simultaneously up the observational ante. The final condition that we should be trying to achieve in our models is not just the distribution of the galaxies, but the distribution of all matter, most of which we have now postulated we do not see.

There is no reason to assume that the galaxies that we see accurately trace the distribution of all matter. They may, for example, trace only the very peaks in a much more complicated distribution of matter. The only way that we can hope to ascertain the true distribution of all matter on large scales is to map it by its gravitational interaction with luminous matter, just as we deduce the presence of galactic halos by studying the orbit of luminous



Monolithic array of 144 "spider-web" bolometers, developed by the author's group. Each of these detectors can determine the temperature of the CMB to 100 millionths of a degree in one second of integration. This device will enable the fine scale structure and polarization of the CMB to be studied in detail over a wide range in frequency.

material in the disk of the galaxy. This is very difficult to do. The velocities of distant galaxies relative to us are primarily due to the expansion. The velocities that allow us to trace inhomogeneities in the matter distribution - the so-called peculiar velocities - are small deviations from the expansion velocity. When we measure the total velocity of a distant galaxy and subtract the expansion velocity, errors in our estimate of how far away the galaxy is, and thus of its true expansion velocity, defeat our ability to accurately determine its peculiar velocity.

One peculiar velocity that we know with fantastic precision, thanks to the CMB, is our own. The gradient in temperature due to our motion determines it to a precision of about 1 km/sec, the precision set by the 10 ppm uniformity of the CMB. The velocity that we measure is 370 km/sec. Without knowing more, we might guess that this velocity, which is typical of the rate at which objects orbit in galaxies, is due to the motion of our Sun around the center of our Galaxy. In fact, this is not the case. When we take into account the known velocity and direction of our Sun around the Galaxy, we find that the entire Galaxy is moving relative to the CMB at close to 600 km/sec. Our next guess might be that the motion of our Galaxy relative to the overall expansion must then be due to its orbit about other galaxies within the Local Group - the cluster of galaxies in which we live. Again we would be wrong. We can measure our motion relative to these Galaxies. These measurements and the direction and amplitude of our velocity deduced from the CMB imply that the entire Local Group is moving with a peculiar velocity of approximately 600 km/sec. This is a large velocity. It indicates that there is an enormous force on the entire Local Group - presumably gravitational attraction towards a large concentration of mass somewhere along the direction of its motion.

A basic principle of cosmology is that the universe is homogenous on large scales - i.e. that if we could map a large enough portion of the universe, then one part of the map would look like, and have the same density, as another part. On the largest scales, there should be no bulk peculiar velocities. The trend that we see locally, on the scale of our own cluster of galaxies - of larger and larger volumes moving at larger and larger velocities, must stop at some point. The amplitude of our cluster is higher than what one would expect today, but it is hard to make much of this fact, since we are only one part of the universe, and could well simply have a higher than average velocity.

Astronomers have attempted to measure the bulk motion of an even larger collection of matter extending in a sphere out to a radius of 600 million light years around us. This measurement is difficult - at this distance the

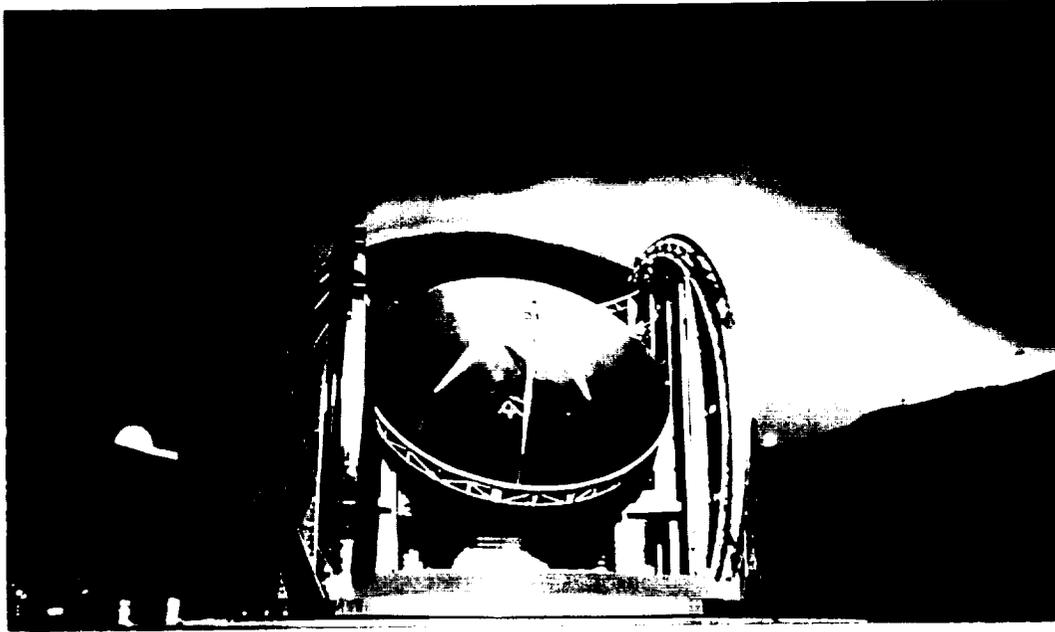
expansion velocity itself is well over 10,000 km/sec – so it is important to estimate the distance to each cluster accurately. A careful job indicates that this entire sphere is moving, still with a peculiar velocity of about 600 km/sec. There is no sign of the scale at which the bulk flow of matter will tend towards zero.

This state of affairs is troubling. Of course, the measurements are difficult, and may be wrong, or our local region of the universe may not be typical. Using conventional astronomical techniques, however, it will be difficult to do much further progress. What is needed is a method for accurately measuring peculiar velocities at great distances, so that we can probe a fair sample of the universe.

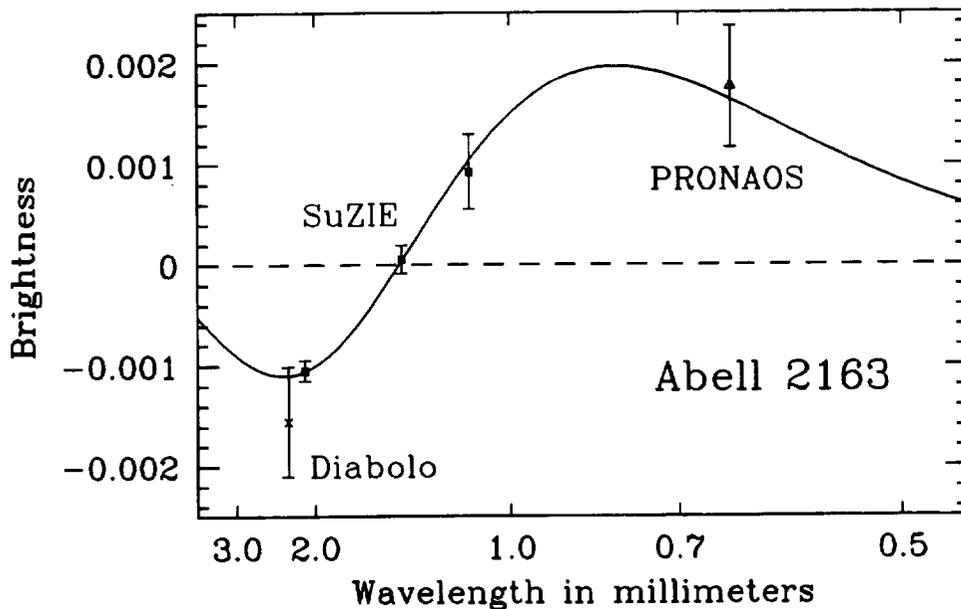
The ideal frame of reference for measuring peculiar velocities is provided, as we have seen, by the CMB. If we had a set of collaborators positioned all through the universe, and if each were to build a COBE and measure their peculiar velocity, then we would have a very high precision map of peculiar velocities, from which we could deduce the underlying distribution of all matter.

Such a collaboration is impractical, yet Nature provides us with a way to do almost as well, using the "margin notes" that have been added to the CMB since decoupling. It is not precisely true that the CMB has never interacted with matter since decoupling. Most clusters of galaxies are filled with a hot ionized plasma that, though less dense than the plasma that filled the early universe, is sufficiently dense that it interacts with about 1% of the CMB photons that pass through the cluster on their way to our telescope. The interaction, known as the Sunyaev-Zeldovich effect, does two things. First, because the photons ($T \sim 3\text{K}$) are much cooler than the plasma ($T \sim$ a million degrees), the photons gain energy in the interaction. The result is to distort the perfect blackbody spectrum of the CMB in a peculiar way. The CMB becomes dimmer at wavelengths longer than about 1.5 mm, and brighter at shorter wavelengths.

The second effect arises not from the thermal motion of the plasma, but from its bulk motion relative to the CMB, i.e. from the cluster's peculiar velocity. Because the cluster scatters about 1% of the CMB photons, we can think of it as a partially reflecting mirror. Most of the CMB that we see comes to us from behind the cluster, but some is reflected by the cluster towards our telescope. If the cluster has a peculiar velocity towards us, then the CMB will appear slightly hotter. If it has a peculiar velocity away from us, then CMB will appear cooler.



The Caltech Sub-millimeter Observatory (CSO) on Mauna Kea in Hawaii. The author's group has used this 10 m telescope and a novel detector system called SuZIE to make the first detections of the Sunyaev-Zeldovich effect at mm wavelengths, and to set tight upper limits to the temperature fluctuations in the CMB on arcminute angular scales. These pioneering measurements have been made during the relatively short periods of observing time available at the CSO. The experience gained from these measurements will be applied to the design of a 6 m telescope in the Chilean Andes that will be outfitted with powerful new detector systems containing hundreds of bolometers and dedicated to observations of the CMB.



Measurements of the Sunyaev-Zeldovich effect in Abell 2163, a rich cluster of galaxies. At wavelengths longer than 1.4 mm, the cluster appears dimmer than the surrounding CMB. At shorter wavelengths it appears brighter. Peculiar motion of the cluster relative to the CMB shifts the null in the spectrum away from 1.4 mm. The measured peculiar velocity is 720 ± 590 km/sec. The expansion velocity is 60,000 km/sec.

The temperature change of the CMB due to the peculiar motion of the cluster can be separated from the (much larger) effect due to the spectral distortion only with measurements made near the special wavelength at which the spectral distortion is zero. With adequate sensitivity and angular resolution, one could ultimately determine the peculiar velocity to a precision of about 150 km/sec, limited by the variations in temperature intrinsic to the CMB on these angular scales.

The Sunyaev-Zeldovich effect has an unusual features that makes it a particularly powerful tool for studying a large volume of the universe. Unlike any other signal that we might try to detect from the distant universe, the spectrum and brightness of the Sunyaev-Zeldovich effect do not change with distance. This is because the CMB itself is hotter, and thus brighter, in the past. The increase in the temperature of the CMB as we look to greater distances, and thus farther back in time, exactly compensates for the decrease in brightness and the "redshift" to longer wavelengths that occurs due to the expansion of the universe. Though measurements of the Sunyaev-Zeldovich effect are difficult to make, when we learn how to make them we immediately open up a vista that extends back in time to the formation of the first clusters.

The first measurements of this kind have already been made, using a specially designed receiver at a 10 m telescope at the top of Mauna Kea, in Hawaii. This prototype experiment has developed the basic techniques necessary to measure the Sunyaev-Zeldovich effects on these angular scales and at these frequencies. It has already succeeded in measuring the peculiar velocity of several clusters that are over 2 billion light years away with a precision far greater than could ever be achieved using conventional astronomical methods. A full survey of the sky is outside the reach of this prototype experiment. We now know enough about how to make the measurements, however, that we can begin to plan in earnest a dedicated telescope equipped with a powerful receiver using large arrays of sensitive detectors. Such an experiment would be able to map the peculiar velocity of distant galaxies with a precision of 150 km/sec – ample to detect the velocity of our own Local Group – over much of the observable universe.

In addition to determining the peculiar velocity field of clusters, and thus the underlying distribution of all matter on the largest scales, the Sunyaev-Zeldovich effect can also be used to measure two other important properties of the late universe: the total number of clusters of various sizes, and the expansion rate of the universe. Although other methods exist for determining each of these, using the Sunyaev-Zeldovich effect enables us to

probe a very large volume of the universe because it has the unique property that it is equally as bright for distant clusters as it is for nearby clusters. Though both of these projects are still in their infancy, they hold much promise.

The various measurements described here – the determination of the amplitude and characteristic scales of both temperature variations and polarization that were imprinted in the CMB at decoupling, a measurement of the peculiar velocity field, and thus of the underlying mass distribution over a large volume of the universe, and the determination of the expansion rate and of the density of clusters of galaxies as a function of time – are all difficult. They will require an enormous amount of careful work. Technology is advancing so rapidly, however, that most or all these goals will be realized in the next 10 to 20 years.

The result will be to revolutionize cosmological science. Many current questions (how old is the universe, will it expand forever, is it made primarily of the forms of matter that we know of, or of something different) will be answered definitively. Other questions (what is the nature of the dark matter, did the early universe undergo a period of inflation) will move from the realm of speculation to scientific inquiry. Finally, questions that are now on the boundary between metaphysics and science (why is there something rather than nothing, what existed previous to the Big Bang, are we one of many universes) may be brought within the bounds of scientific inquiry.

Humans have always speculated about what lies beyond the furthest extent of our vision, often projecting our inner world into the farthest reaches. This ancient tendency persists unabated today. Human interest in the cosmos is deep and complex. It is here that our instinct and hunger for scientific and spiritual inquiry intersect most strongly.

Twenty years from now, we can hope to have explored the CMB in detail. Like the intrepid explorer on the cover of this essay, we will have succeeded in peering beyond the most distant stars. When we complete our exploration of the CMB, we will have pushed our vision literally to the edge of the universe.

What will be the effects on society? The scientific story of the creation and evolution of the Universe – one of the greatest tools that we as scientists have at our disposal to interest the public, and especially to inspire children and young adults – will be made far richer. We will have a profoundly deeper understanding of the connection between the very small and the very

WEEKLY WORLD

NEWS

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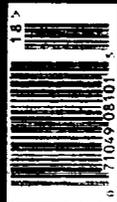
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**SPECIAL NEWS
BULLETIN
FROM NASA:**

HEAVEN PHOTOGRAPHED BY HUBBLE TELESCOPE



*'We found
where God
lives,' says
scientist!*



Modern interest in cosmology takes many forms. Mankind's long association of the cosmos with spirituality continues to reverberate today in various forms, from the sublime to the ridiculous. "Heaven" has historically resided just beyond the reach of our vision. CMB measurements extend that reach to the edge of the universe. The challenge for modern cosmologists is to replace the ideas illustrated here with a the deeper and more profound sense of awe and wonder which is due the beauty of the universe that we have discovered.

large – how microscopic quantum effects may have determined the large scale structure of the present universe. We will discover the ultimate fate of the universe, and discover why it has the rich variety of structure in that we observe today. We may well find out that we are not only not at the center of the universe, but that we are not even made of the stuff that most of the universe is made of – the ultimate Copernican Revolution.

Acknowledgments: I am indebted to many colleagues and students who have contributed to the ideas presented here, among whom Jamie Bock and Sarah Church deserve special mention. I am grateful for the interest in and support for this work that I have received from Michael Bicay, Alan Bunner and Harley Thronson through the NASA Structure and Evolution of the Universe theme, from Charles Elachi and Virendra Sarohia through the NASA Jet Propulsion Laboratory, from Ben Snavely through the NSF Advanced Technology and Instrumentation Program, from Sethanne Howard through the NSF Extragalactic Astronomy program, from Bernard Sadoulet and Marc Davis through the NSF Center for Particle Astrophysics, and from the David and Lucile Packard Foundation.



